A new phenomenon in heavy ion inelastic scattering

Scarpaci, JA; Beaumel, D; Blumenfeld, Y; Chomaz, P; Frascaria, N; Jongman, J; Lacroix, D; Laurent, H; Lhenry, I; Marechal, F

Published in:
Physics Letters B

DOI:
10.1016/S0370-2693(98)00437-7

4 June 1998

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 428 (1998) 241–247

A new phenomenon in heavy ion inelastic scattering: the towing mode [1]

J.A. Scarpaci [a], D. Beaumel [a], Y. Blumenfeld [a], Ph. Chomaz [b], N. Frascaria [a], J. Jongman [a], D. Lacroix [b], H. Laurent [a], I. Lhenry [a], F. Maréchal [a], V. Pascalon-Rozier [a], P. Roussel-Chomaz [b], J.C. Roynette [a], T. Suomijärvi [a], A. Van der Woude [c]

[a] *Institut de Physique Nucléaire, IN2P3-CNRS, 91406 Orsay, France*
[b] *GANIL, BP 5027, 14076 Caen Cedex 5, France*
[c] *Kernfysisch Versneller Instituut, 9747 AA Groningen, The Netherlands*

Received 15 December 1997; revised 23 March 1998
Editor: R.H. Siemssen

Abstract

The inelastic scattering of ^{40}Ar on ^{58}Ni has been studied at 44 MeV per nucleon incident energy in coincidence with light particle emission. Besides the well known mechanisms of inelastic excitation, pick up break up and nucleon knock out, a new phenomenon has been observed, giving rise to fast forward moving particles with specific angular correlations. This newly observed mechanism seems to be a generic phenomenon present for various projectile-target combinations and incident energies. Its contribution to the inelastic spectrum has been extracted and a tentative interpretation is given. © 1998 Elsevier Science B.V. All rights reserved.

PACS: 25.70.Bc; 25.70.Hi; 25.70.Pq; 24.10.-i

Inelastic scattering of heavy ions has been extensively used to study nuclear structure. In particular, the excitation and decay of giant resonances and multiphonon states has been investigated to infer information on their microscopic nature [1]. In addition to collective excitations of the target, the decay of which gives rise to isotropically emitted low energy particles, two other processes are known to contribute to the inclusive inelastic scattering spectrum: nucleon knock-out and pick-up break-up. At incident energies around 50 MeV per nucleon, these different reactions can be well separated by measuring light charged particles in coincidence with the inelastically scattered projectiles [2]. The quasi elastic knock out process gives rise to particles emitted around the direction of the recoiling target nucleus. This mechanism, known to be a major contribution to inelastic scattering of protons and α-particles, has been seen to persist in heavy ion induced scattering, but the shape and the strength of its contribution to the ejectile energy spectrum has not been quantita-

[1] Experiment performed at the GANIL national facility, Caen, France.

PII: S0370-2693(98)00437-7

tively extracted so far. The pick-up break-up mechanism, described in Ref. [3], is a two step process. The projectile picks up a nucleon from the target, leaving it in a 1-hole configuration, and then breaks up by emitting one nucleon, thus feeding the inelastic channel. The velocity of the emitted nucleon is boosted by the projectile velocity, leading to the emission of the nucleon in a narrow cone around the direction of the scattered projectile, which is in our case detected at angles smaller than 5 degrees. The opening angle of this cone is approximately 30 degrees in the case of proton emission from a mass 40 projectile at 50 MeV per nucleon [2], and is expected to be smaller in the case of neutron emission due to the absence of the Coulomb barrier. In the ejectile energy spectrum, this process gives rise to an approximately flat shaped contribution over an excitation energy interval centered slightly above the bombarding energy per nucleon and with a width determined by the specific decay characteristics of the system [3].

During the course of systematic studies of heavy ion inelastic scattering [4–6], it was found that in addition to the three processes alluded to above, there is a fourth mechanism occurring as a result of the collision process. This new process gives rise to particles emitted in the forward hemisphere exhibiting very specific angular correlations. However, in these previous experiments, the angular coverage for light particles was not optimized for the study of this mechanism. To enhance our understanding of the inelastic channel in heavy ion reactions, a detailed study of this process is called for.

We report here on the ^{58}Ni(^{40}Ar, ^{40}Ar + n or p) inelastic scattering reaction performed at 44 MeV per nucleon, in which the particle decay to the ground state (GS) and the low-lying excited states of the daughter nucleus exhibits an anomalous behaviour. We find that the most energetic decay particles are focused in a narrow cone in a direction which is not compatible with any of the known reaction mechanisms described above. In-plane and out-of-plane angular correlations between the ^{40}Ar ejectile and the emitted particles will be presented in order to characterize the new mechanism, named ‘‘towing mode’’. Its contribution to the inclusive inelastic spectrum will be extracted and an interpretation will be suggested.

The experiment was performed at the GANIL facility by bombarding a 1 mg/cm^2 ^{58}Ni target with the 44 MeV per nucleon ^{40}Ar beam. Protons were detected in 28 cesium iodide (CsI) elements of the multidetector array PACHA [7]. Most of these detectors were located on two rings centered on the target at a distance of 12 cm. The detectors were placed out of the horizontal plane at out of plane angles of $-30°$ and $-50°$. Unambiguous identification of protons was obtained through shape analysis of the CsI pulse. The energy resolution was 2% above 20 MeV and around 6% for protons of energy less than 10 MeV.

Neutrons were detected with the liquid scintillator array EDEN [8] consisting of 45 modules positioned at about 1.75 meters from the target at angles running from 35° to 290°. In-plane angles are counted clockwise, 0° corresponding to the beam direction. The neutron identification was performed through a pulse shape analysis and the energy was obtained by a time of flight measurement that yielded an energy resolution of about 500 keV for 6 MeV neutrons and 2 MeV for 16 MeV neutrons. All the data in coincidence with neutrons were corrected for the detection efficiency according to Ref. [8].

The ejectiles were detected with the SPEG spectrometer [9] centered at $\Theta_{lab} = 3°$ and equipped with its standard detection system, consisting of two position sensitive drift chambers, an ionization chamber and a plastic scintillator. Both the horizontal and vertical opening angles are $\pm 2°$. An unambiguous identification of the ejectile was obtained from an energy loss measurement in the ionization chamber combined with a time of flight measurement which yielded the charge and the mass over atomic charge ratio of the ejectile, respectively. During the analysis a software gate was set on ^{40}Ar to select the inelastic channel. Using the momentum and the scattering angle of the ejectile deduced from the reconstructed trajectory and applying two body kinematics, we calculate for each event an ‘‘apparent’’ excitation energy E^*. This energy corresponds to the total deposited energy in the case of inelastic excitation of the target. The energy resolution obtained was 800 keV. The missing energy is calculated as follows: $E_{miss} = E^* - E_p - E_{rec}$ where E_p and E_{rec} are the kinetic energies of the detected particle and of the recoiling nucleus respectively. In the case where only one light particle is emitted in the reaction, the missing energy is related to the final state energy of the target nucleus E_{fs} by $E_{fs} = E_{miss} + Q$, where Q is the reaction Q-value.

Fig. 1 shows the missing energy spectra obtained for proton (a and c) and neutron (b and d) decay respectively, for excitation energies above 30 MeV and for two groups of detectors, one at backward angles in the laboratory frame and the other one in the forward direction, on the same side of the beam as the ejectile as sketched on the figure. For both detector groups, a large bump around 30 MeV is observed which corresponds to the decay of the target. At forward angles (between 30° and 85°) an important additional contribution feeding the GS and the first excited states of the daughter nuclei is present.

In order to study the angular correlations of decay particles populating the low-lying states of these nuclei, a 4 MeV wide gate was set on missing energies around the GS of the daughter nuclei, 12 MeV and 9 MeV for ^{57}Ni and ^{57}Co respectively, as shown on Fig. 1. These correlations are presented on Fig. 2 for the full acceptance of the spectrometer. The neutron angles are shown in the laboratory system. Most of the proton detectors are located out-of-plane and we have chosen to plot the proton angular distributions as a function of the angle in the horizontal plane. The correlations are plotted for apparent excitation energies between 12 MeV (16 MeV for protons) and 80 MeV. Besides an almost isotropic component which could result from the decay of the target, a very strong peak is observed around $+40°$ on the same side of the beam as the ejectile. A fit, including a flat background and a Gaussian, has been performed. The amplitude of the Gaussian peak is much larger for neutrons than for protons. It is located at angles larger than what is expected for pick up break up reactions and on the opposite side of the beam from knocked out nucleons. In the proton angular correlation we also observe, located around $-60°$ on the opposite side of the beam from the ejectile, the recoil protons coming from the elastic scattering from the hydrogen contained in the target, and possibly also from a contribution of the knock-out process.

Further insight into the emission mechanism of the particles can be given by azimuthal angular correlations. Such correlations could be extracted as the ejectile was detected at azimuthal angles located between $\Phi_{eject}^{spher} = \pm 50°$, where $\Phi^{spher} = 0$ is taken in the horizontal plane on the right side of the beam where the ejectile is detected. Most proton detectors were positioned outside of the horizontal plane, Φ_{prot}^{spher} around $-37°$ for detectors on the right side of the beam and Φ_{prot}^{spher} around $-143°$ for detectors on the left side of the beam. Fig. 3(a) presents the spherical angles of ejectiles, Φ_{eject}^{spher} and Θ_{eject}^{spher}, in

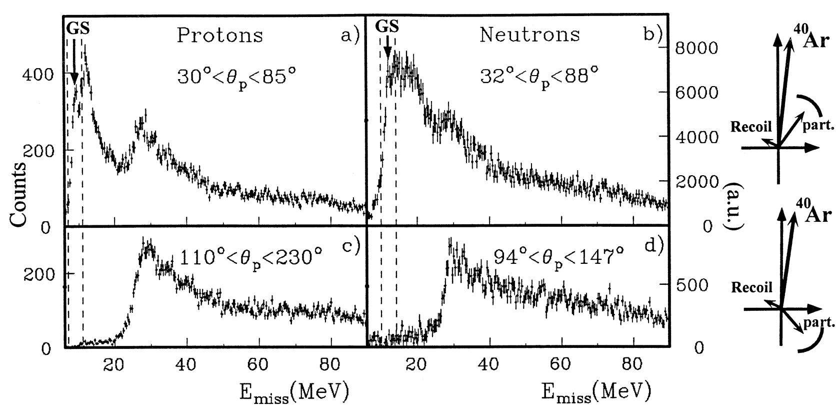

Fig. 1. Missing energy spectra for excitation energies above 30 MeV for forward ((a) and (b)) and backward ((c) and (d)) emitted particles. The missing energy spectra in coincidence with neutrons were corrected for the neutron detection efficiency. For each particle type, the two spectra are normalized to the same detector solid angle. The right side of the figure shows a sketch of the ejectile velocity after scattering, the emitted particle velocity and the velocity of the undetected recoiling target. Dashed vertical lines represent the gates as set for the angular correlations presented in Fig. 2.

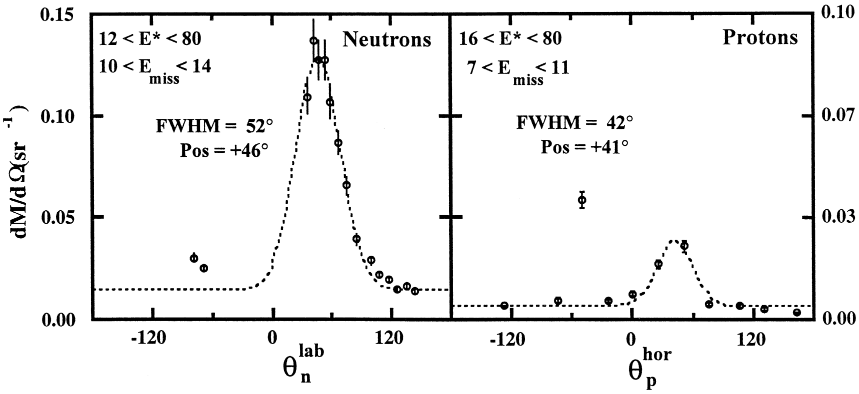

Fig. 2. Neutron and proton angular correlations for particles feeding the GS of the daughter nucleus (between 7 and 11 MeV in the missing energy spectrum for the protons and 10 and 14 MeV for the neutrons (see Fig. 1)) and for apparent excitation energies below 80 MeV. The dashed lines are the result of a fit with a Gaussian peak plus a constant background. The characteristics of the Gaussian are reported.

coincidence with backward emitted protons coming from the target decay. The shape of this scatterplot simply reflects the square entrance of the SPEG spectrometer located on the right side of the beam. Even though the protons were detected out of the horizontal plane, the azimuthal angular distribution is symmetric around $\Phi_{eject}^{spher} = 0$ demonstrating that there is no correlation between the particles arising from the target decay and the direction of the scattered projectile. Fig. 3(b) shows the same two-dimensional spectrum for ejectiles in coincidence with protons stemming from the elastic scattering on the hydrogen contaminent in the target. As the proton is detected around $\Theta_{prot}^{spher} = 56°$ and $\Phi_{prot}^{spher} = -143°$ (on the left side of the beam), the ejectile is observed around $\Phi_{eject}^{spher} = +37°$ as expected for a binary reaction. The insert of Fig. 3(b) schematically depicts the velocity of the elastically scattered ejectile (full dot) and of the emitted proton (open dot) in the plane perpendicular to the beam velocity (crossed circle). Fig. 3(c) shows the scatterplot of ejectiles in coincidence with protons feeding the GS and the first excited states of

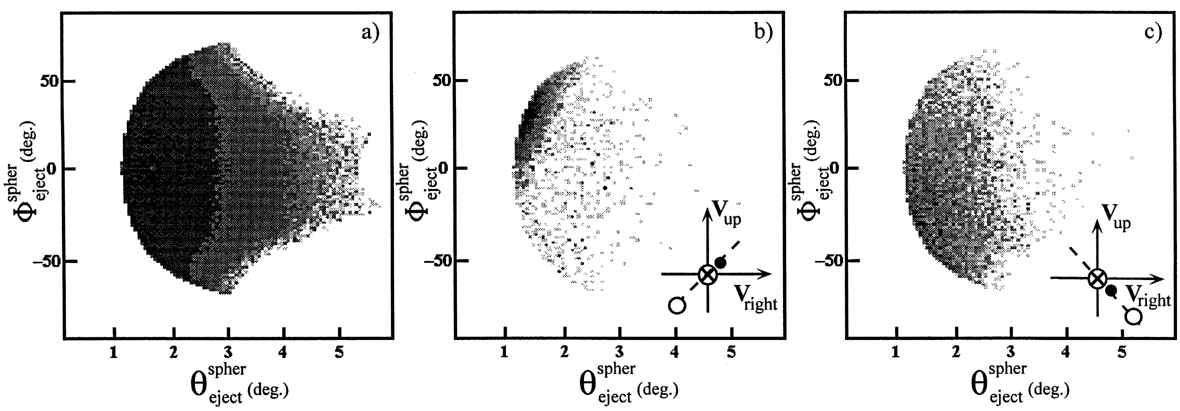

Fig. 3. Angular distribution (Φ_{eject}^{spher} and Θ_{eject}^{spher}) for the ejectile in coincidence with backward emitted protons (a), protons coming for the scattering on the hydrogen of the target (b) and protons feeding the GS of ^{57}Co and emitted around $\Theta_{prot}^{spher} = 40°$ and $\Phi_{prot}^{spher} = -43°$ (c). Inserts of panels (b) and (c) schematically depict the velocities of the ejectile (full dot) and of the proton (open dot) in the plane perpendicular to the beam axis (represented as a crossed circle), for the elastic scattering (b) and for the new mechanism (c).

the daughter nucleus (^{57}Co) and emitted around $\Theta_{prot}^{spher} = 45°$ and $\Phi_{prot}^{spher} = -43°$, corresponding to the mechanism of interest. Contrary to Fig. 3(a), a strong correlation between the proton and the ejectile azimuthal angles is observed. However here, the ejectile and the proton are both detected below the horizontzal plane, at about the same azimuthal angle, $\Phi_{eject}^{spher} = -43°$, as schematically summarized in the insert.

These strong correlations, both in-plane and out-of-plane, between the particle and the ejectile velocities, combined with the information that the particle energies are on the average close to half of the beam energy per nucleon, suggest an interpretation of the particle emission mechanism in terms of an aborted pick-up. It seems that the particle is extracted from the target and towed along for a short while by the ejectile. Therefore we name this mechanism ''Towing Mode''.

The contribution of this mechanism to the inclusive inelastic spectrum can be extracted by comparing the inelastic spectra in coincidence with forward emitted particles (between $+35°$ and $+70°$), where the contribution from towing mode particles is present, with the one in coincidence with backward emitted particles (between $+120°$ and $+170°$), which stem solely from target decay, with no cut on the ejectile angle. The extracted contribution, shown on Fig. 4, is peaked at an apparent excitation energy of about 30 MeV for both neutrons and protons and extends as far as 80 MeV. It is interesting to note that the neutron contribution is an order of magnitude larger than the proton contribution. This could be due to the structure of ^{58}Ni composed of two valence neutrons around the closed shell ^{56}Ni core or to the Coulomb barrier.

A tentative normalization to the inclusive inelastic spectrum has been performed as follows. The angular correlations were extracted with no constraint on the excitation energy nor on the missing energy. They were then fitted by a Gaussian plus a constant background, and the Gaussian curves were integrated assuming an azimuthal angle running between $\pm 50°$ which corresponds to the azimuthal opening angle of the spectrometer, giving the total number of counts for the mechanism (this is based on the assumption that the projectile and the emitted particle have the same azimuthal angle). Fig. 4 shows the inclusive

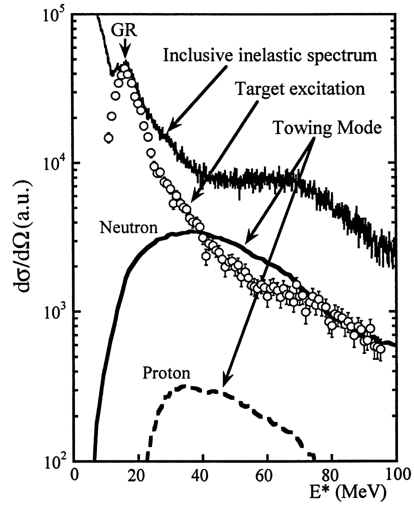

Fig. 4. Inclusive inelastic spectrum (top) displayed together with the contribution of the new mechanism (plain and dashed lines). Dotted spectrum is the contribution of the excitation of the target.

inelastic spectrum (top) as well as the extracted contribution for the new mechanism, for both neutron (solid line) and proton (dashed line) emission. The shape of the spectrum reflects the kinetic energy distribution of the light emitted particles. Also shown is the inelastic spectrum in coincidence with backward emission of neutrons or protons normalized to 4π that reflects the excitation of the target (open dot spectrum). Above 40 MeV the contribution of the new mechanism is of the same order of magnitude as that of target excitation. In the reaction studied, it contributes for about 20% of the total inelastic cross section in the excitation energy region of 20 to 100 MeV. The additional strength observed in the inclusive spectrum must be mainly due to the pick-up break-up mechanism [10].

This experiment shows that in this new process the target nucleus is left in a 1-hole state (cf. missing energy spectra, Fig. 1), just as in the pick-up break-up and the knock-out processes. However the transferred nucleon does not form a short-lived unbound system with the projectile and thus is not fully boosted to the projectile velocity. The angular correlations (Fig. 2 and Fig. 3) show that the direction of the particle is strongly correlated to that of the ejectile but does not correspond to what is expected either for the pick-up break-up process or for the knock-out process. The ‘‘Towing Mode’’, seems to be a general phenomenon in heavy ion scattering since a similar component of fast forward moving particles has been observed in many other inelastic scattering experiments , ^{208}Pb (^{17}O, ^{17}O + n) [5], ^{40}Ca (^{40}Ca, ^{40}Ca + p) [4], ^{48}Ca (^{20}Ne, ^{20}Ne + n) [11], ^{90,94}Zr (^{36}Ar, ^{36}Ar + n) [6] at incident energies between 40 and 84 MeV per nucleon. Even at incident energies as high as 400 MeV per nucleon, fast forward moving neutrons were observed in the reaction ^{nat}Xe (^{17}O, ^{17}O’ + n) [12]. The authors of Ref. [12] interpreted this fast component as knock-out of neutrons in the far-out region of the nucleus, i.e. in the nuclear stratosphere. However, the out-of-plane correlation measured in our experiment tells us that the fast particles that we observe are not coming from a knock-out process since it would then resemble the elastic scattering azimuthal correlation, hence completely opposite to what we observe.

To investigate if a model can qualitatively explain our observations, a calculation has been performed to infer the evolution of a particle wave function when two potentials brush past each other. The time dependent Schrödinger equation was solved in a two dimentional space using Wood-Saxon potentials of radii $r = 1.2 \cdot A^{1/3}$ and diffuseness $a_0 = 0.5$ Fermi. It describes the evolution of a wave function initially in the target potential at rest when the projectile passes by at a given impact parameter. Since we are dealing with very peripheral reactions in which both the target and the projectile are very little disturbed (they remain mostly cold after the collision), we assumed constant wells. Fig. 5 shows the probability density for a 2s wave function initially bound in the target potential by 8.7 MeV, when the projectile has passed by at an impact parameter of 8 Fermi at an incident energy of 44 MeV per nucleon. We observe that there is a large probability that the particle remains in the target (73%), and some probability that it is transfered to the projectile (1.4%). But most interesting is the sizeable probability (21%) of particle emission at an angle around 50° on the same side of the beam as the projectile, qualitatively reproducing the experimental observation. This calculation will be more extensively discussed in a forthcoming paper.

Summarizing, we have observed and characterized a new phenomenon in the inelastic channel of heavy ion collisions at intermediate energies. This process consists in the emission of a fast nucleon leaving the residual nucleus in the GS or a low-lying hole state. The angular characteristics of the emitted particle, which are inconsistent with what is expected from either the pick-up break-up or the nucleon knock-out mechanisms, support an interpretation in terms of an aborted transfer where the nucleon in towed by the projectile for a very short period of time and then emitted into the continuum. A calculation solving the time dependent Schrödinger equation predicts a similar emission of particles in the same spatial region. Future experiments, with a more complete angular coverage for light particles, should investigate the dependence of this phenomenon on the projectile-target combination, the incident velocity and the initial angular momentum of the emitted particle in order to further our quantitative understanding of this new phenomenon.

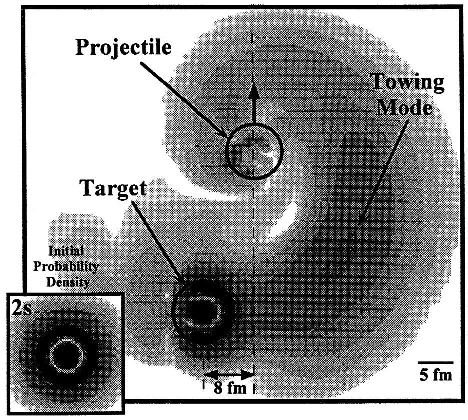

Fig. 5. Result of the time dependent Schrödinger calculation. Probability density of a 2s wavefunction initially in the target, after the scattering of a 44 MeV per nucleon projectile at 8 Fermi impact parameter. The two circles have the radii of the target (A = 58) and the projectile (A = 40) Wood-Saxon wells. The insert is the wavefunction probability density prior to the scattering.

References

[1] Ph. Chomaz, N. Frascaria, Phys. Rep. 256 (1995) 275.
[2] J.A. Scarpaci et al., Phys. Lett. B 258 (1991) 279.
[3] Y. Blumenfeld, J.C. Roynette, Ph. Chomaz, N. Frascaria, J.P. Garron, J.C. Jacmart, Nucl. Phys. A 445 (1985) 151.

[4] J.A. Scarpaci et al., Phys. Rev. C 56 (1997) 3187.
[5] A.M. van den Berg et al., Nucl. Phys. A 578 (1994) 238.
[6] V. Pascalon, Ph.D. thesis, Université d'Orsay, France, report IPNO-T-97-01, 1997.
[7] J.A. Scarpaci, Ph.D. thesis, Université d'Orsay, France, report IPN0-T-90-04, 1990.
[8] H. Laurent et al., Nucl. Inst. Meth. in Phys. Res. A 326 (1993) 517.
[9] L. Bianchi et al., Nucl. Inst. Meth. in Phys. Res. A 276 (1989) 568.
[10] J.A. Scarpaci et al., in: E. Gadioli (Ed.), Proceedings of the 8th International Conference on Nuclear Reactions, Varenna, Italy, 1997, Ricerca Scientifica ed Educazione Permanente, Supplemento 111, p. 351.
[11] H. Laurent et al., Nouvelles du GANIL, December 1994.
[12] A. Ringbom et al., Nucl. Phys. A 621 (1997) 879.